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Improved Performance of Silicon Carbide Detector Using Double Layer Anti Reflection (AR) Coating

by N. C. Das, A. V. Sampath, H. Shen, and M. Wraback

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14. ABSTRACT

Avalanche photodiodes fabricated on a silicon carbide (SiC) substrate showed peak responsivity near 280 nm. The SiC detector structure is grown epitaxially on a 2-µm-thick n-type bottom contact layer followed by a 0.48-µm lightly doped multiplication layer and a top heavily doped 0.45-µm p-type contact layer. Double-layer anti-reflection (AR) coating is grown by a plasma enhanced chemical vapor deposition (PECVD) technique at 250 °C. Using a double-layer AR coating with a bottom silicon nitride (Si_3N_4) layer and a top silicon dioxide (SiO_2) layer broadly enhanced responsivity in the full detector spectral range. We observed that the enhancement of the detector responsivity by using double-layer AR coating is higher than the enhancement observed in a similar device with a single-layer AR coating with a SiO_2 film. We observed about 28% increases in detector responsivity by using a double-layer AR coating.

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1. Introduction

In recent years, a great deal of research effort has been focused on detecting low-level ultraviolet (UV) light using avalanche photodiodes (APDs). As the number of applications for UV solid-state detectors increases in civilian and military fields, such as flame detection, chemical analysis, determination of engine combustion efficiency, and biological agent sensing, it is critical that these devices meet ever more stringent performance specifications. Competing material technologies such as silicon (Si), gallium nitride (GaN), aluminum gallium nitride (AlGaN), and silicon carbide (SiC) have all shown promising aspects as well as challenges. Since Si possesses low responsivity in the UV region and AlGaN has a high defect density, a 4H-SiC polytype material has emerged as an attractive candidate. Previously, linear-mode 4H-SiC APDs have demonstrated a very low dark current, high avalanche gain, and low excess noise (*1, 2*). Recently, these SiC APDs have also demonstrated high sensitivity, single-photon counting. In Geiger mode, 30% single-photon detection efficiency at 280 nm and a low dark count probability at room temperature were achieved (*3*).

SiC APDs have another important application: to replace the bulky, high-power photo multiplier tube. Many techniques have been adopted to increase the sensitivity of SiC APDs, including varying the epitaxial-structural design of the absorption layer and deposition of a nano-plasmonic structure on the detector active area. Using a single layer of silicon dioxide (SO_2) film as an anti-reflection (AR) coating, Liu et al. (*4*) observed a 20% increase in detector responsivity. We report here the enhanced performance of a SiC detector using a double-layer AR coating (*4*) consisting of silicon nitride (Si_3N_4) and SO_2 layers.

2. Experimental

The 4H-SiC wafer from which the photo detectors were fabricated consists of an n-doped 4H-SiC substrate and the following three epitaxial layers, from bottom to top: a 2000-nm n+ buffer layer ($N_D = 3.0 \times 10^{18}$ cm^{-3}), 480-nm p- layer ($N_A = 2.8 \times 10^{15}$ cm^{-3}), a 200-nm p layer ($N_A = 2.4 \times 10^{18}$ cm^{-3}), and a 100-nm p+ cap layer ($N_A = 4x\ 10^{19}$ cm^{-3}). We fabricated the detectors using double mesa isolation techniques to achieve a high avalanche breakdown voltage. After the reactive ion etching (RIE) of both the mesa structures, we added both the top and bottom metal contacts by e-beam evaporation technique. We used 500 nm of a plasma-enhanced chemical vapor deposition (PECVD)-grown SiO_2 film to passivate the sidewalls and improve the high avalanche breakdown voltage. Following contact window opening, we added interconnect metal structures consisting of titanium (Ti)/gold (Au) metal film to connect the n-and p-contacts to probe pads outside the device active area. A photograph of fully processed SiC wafer with a variable detector device is shown in figure 1.

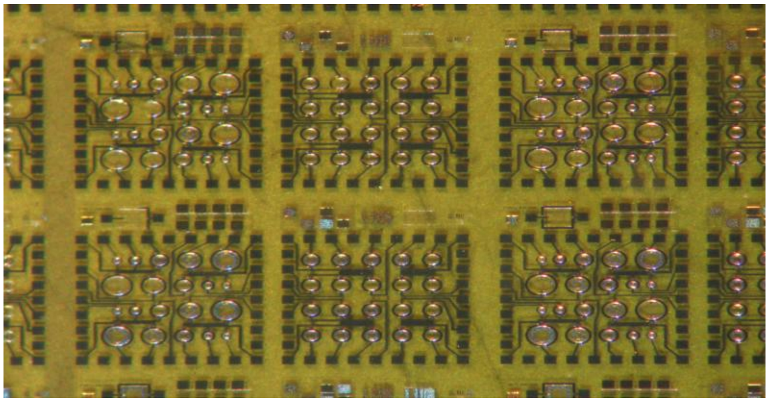

Figure 1. SiC processed detector wafer.

We processed two types of detector arrays. One array consisted of a detector that had the same size (100 µm) device and another consisted of device that varied in size from 50–200 µm diameters. The mask pattern also contains various test structures, like transmission line measurement (TLM) patterns, for contact resistance measurement and pads for implantation profile measurement.

3. Results and Discussions

We used a computer-aided data acquisition system to measure the device characteristics including current-voltage (I-V) curves as well as detector responsivity. Figure 2 shows both forward and reverse I-V curves for different mesa size devices. As it is seen in the figure, the devices have a breakdown voltage greater than 150 V (no avalanche breakdown occurs for a reverse bias <150 V) and a forward turn-on voltage of 3.0 V. However, the device with a 150-µm mesa has a higher leakage current at about 120 V. This may be due to localized point defects for this particular device, as we do not see similar leakage current levels in other devices with the same size mesa. All these devices have very good turn-on characteristics with a turn-on voltage around 3.0 V. Another important observation is that the breakdown voltage is independent of mesa size. We didn’t observe leakage current dependence on mesa sizes. It may be due to the limitation of our experimental setup.

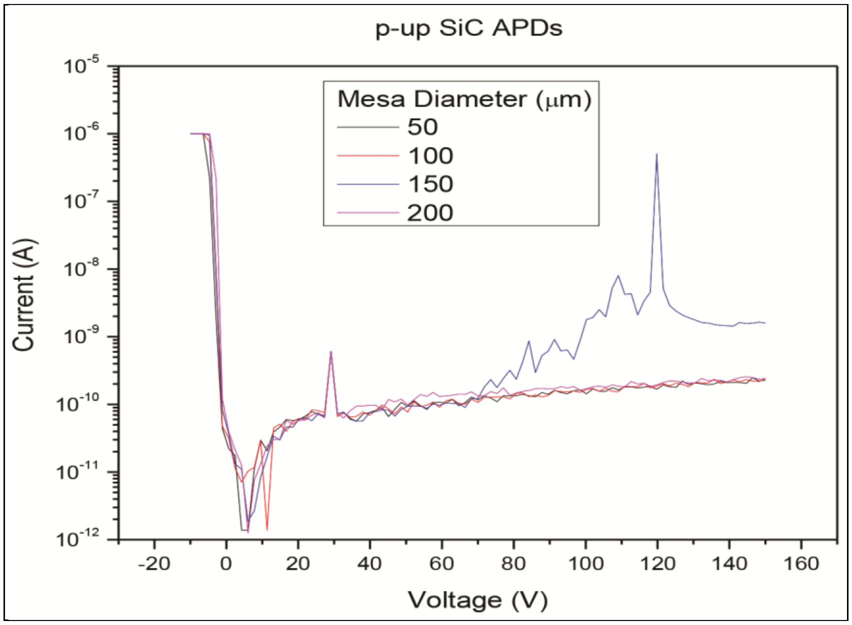

Figure 2. I-V curves of different mesa size devices.

AR coatings on SiC APDs consist of a thin layer of dielectric material of a specially chosen thickness so that the interference effects in the coating cause the wave reflected from the AR coating's top surface to be out of phase with respect to the wave reflected from the semiconductor surfaces. These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy. The thickness of the AR coating is chosen such that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave. For a quarter-wavelength AR coating of a transparent material with a refractive index n_1 and light incident on the coating with a free-space wavelength λ_0, the thickness d_1, which causes minimum reflection, is calculated by

$$d_1 = \frac{\lambda_0}{4n_1} \tag{1}$$

Reflection is further minimized if the refractive index of the AR coating is the geometric mean of that of the materials on either side, that is, glass or air and the semiconductor. This is expressed by

$$n_1 = \sqrt{n_0 n_2} \tag{2}$$

The reflectance of the incident light is a function of thicknesses of the AR coating layer, the incidence angles, and the refractive index of the medium. Figure 3 shows the simulated reflection coefficients for different Si_3N_4 and SiO_2 film thicknesses. We observed minima in the reflection curve for the AR coating layer consisting 150 Ang. of Si_3N_4 and 250 Ang. of SiO_2 at a 270-nm wavelength. Reflectance increases at higher or lower wavelengths of the minima. The simulation results for other combinations of different thicknesses of Si_3N_4 and SiO_2 have minima at different wavelengths. However, the simulation curve for double-layer AR coating consist of 150 Å of Si_3N_4 and 250 Å of SiO_2 has a considerably lower reflectance in a broad range of wavelength regions. Double-layer AR coating has less than 15% reflection in the entire UV spectral region of the SiC detectors. The results presented in figure 3 were obtained using optimized film parameters for minimum reflection in the entire UV spectral region. During simulation, our goal is to use the film parameters to achieve enhancement in the entire detector responsivity region.

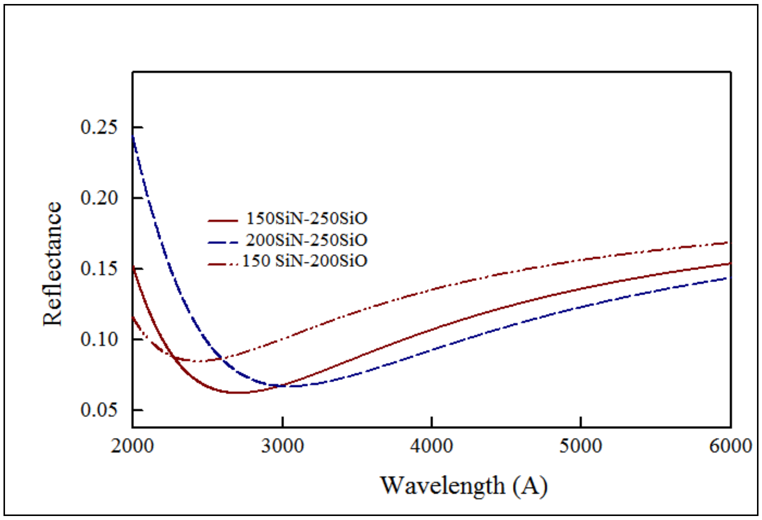

Figure 3. Reflectance simulation curve for different combination of Si_3N_4 and SiO_2 films.

In figure 4, we have shown the experimental detector responsivity data for different AR coatings. We have also shown the data from a control sample showing the responsivity before adding any AR coating. As the results show in figure 4, it is advisable to use a double-layer AR coating as we observed enhanced responsivity in the entire spectral regions. We have not done any annealing after PECVD of the AR coating and believe an experiment with different annealing conditions could be rewarding as it will reduce the interface defects created during PECVD deposition.

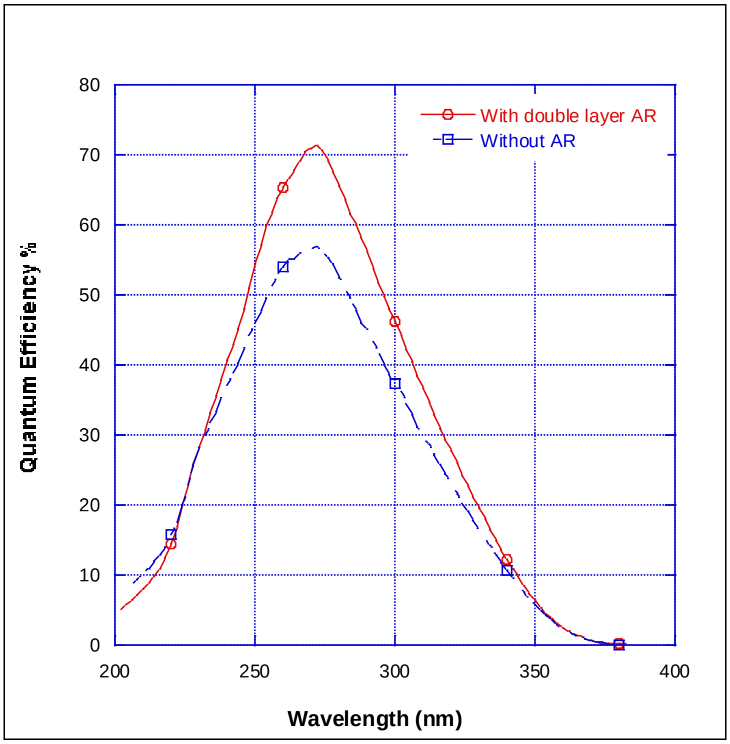

Figure 4. Experimental quantum efficiency curves for detector with and without AR coating.

4. Conclusions

We simulated the double-layer AR coating characteristics with minima in the UV region for enhanced SiC detector performance. Experimentally, we found that a double-layer AR coating consisting of 150 Å of Si_3N_4 and 250 Å of SiO_2 is suitable for AR coating for a broad range of UV detector responses. We observed about 25% increases in detector responsivity by using a double-layer AR coating near the peak wavelength of the detector at 280 nm.

5. References

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List of Symbols, Abbreviations, and Acronyms

AlGaN	aluminum gallium nitride
APDs	avalanche photo diodes
AR	anti-reflection
Au	gold
GaN	gallium nitride
I-V	current-voltage
PECVD	plasma-enhanced chemical vapor deposition
RIE	reactive ion etching
Si	silicon
Si_3N_4	silicon nitride
SiC	silicon carbide
SO_2	silicon dioxide
Ti	titanium
TLM	transmission line measurement
UV	ultraviolet

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